USER'S MANUAL FOR TWO DIMENSIONAL FDTD VERSION TEA AND TMA CODES FOR SCATTERING FROM FREQUENCY-INDEPENDENT DIELECTRIC MATERIALS

by

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I. INTRODUCTION

The Penn State Finite Difference Time Domain Electromagnetic Scattering Code Versions TEA and TMA are two dimensional numerical electromagnetic scattering codes based upon the Finite Difference Time Domain Technique (FDTD) first proposed by Yee [1] in 1966. The supplied version of the codes are two versions of our current two dimensional FDTD code set. This manual provides a description of the codes and corresponding results for the default scattering problem. The manual is organized into eleven sections: introduction, Version TEA and TMA code capabilities, a brief description of the default scattering geometry, a brief description of each subroutine, a description of the include files (TEACOM.FOR TMACOM.FOR), a section briefly discussing scattering width computations, a section discussing the scattering results, a sample problem setup section, a new problem checklist, references and figure titles.

II. VERSION TEA AND TMA CODE CAPABILITIES

The Penn State University FDTD Electromagnetic Scattering Code Versions TEA and TMA have identical capabilities except the TEA code has electric field perpendicular to the z axis and the TMA code has electric field parallel to the z axis. Each code has the following capabilities:

1) Ability to model lossy dielectric and perfectly conducting scatterers.

2) First and second order outer radiation boundary condition (ORBC) operating on the electric fields for dielectric or perfectly conducting scatterers.

3) Near to far zone transformation capability to obtain far zone scattered fields.

4) Gaussian and smooth cosine incident waveforms with arbitrary incidence angles.

5) Near zone field, current or power sampling capability.

6) Companion codes for computing scattering width.

III. DEFAULT SCATTERING GEOMETRY

The codes as delivered are set up to calculate the far zone backscatter fields for an infinite, 0.25 m radius, perfectly conducting cylinder. The problem space size is 201 by 201 cells in the x and y directions, the cells are 1 cm squares, and the incident waveform is a Gaussian pulse with incidence angle of ϕ=180 degrees. The output data files are included as a reference along with codes (SWTEA.FOR, SWTMA.FOR) for computing the

frequency domain scattering width using these output data files. The ORBC is the second order absorbing boundary condition set forth by Mur [2].

IV. SUBROUTINE DESCRIPTION

In the description for each subroutine, an asterisk (*) will be placed by the subroutine name if that particular subroutine is normally modified when defining a scattering problem. Also, each subroutine will be denoted if it is applicable to the TE code only, the TM code only, or to both codes.

MAIN ROUTINE (TE, TM)

The main routine in the program contains the calls for all necessary subroutines to initialize the problem space and scattering object(s) and for the incident waveform, far zone transformation, field update subroutines, outer radiation boundary conditions and field sampling.

The main routine begins with the include statement and then appropriate data files are opened, and subroutines ZERO, BUILD and SETUP are called to initialize variables and/or arrays, build the object(s) and initialize the incident waveform and miscellaneous parameters, respectively. Subroutine SETFZ is called to intialize parameters for the near to far zone transformation if far zone fields are desired.

The main loop is entered next, where all of the primary field computations and data saving takes place. During each time step cycle, the EXSFLD (TE), EYSFLD (TE), and EZSFLD (TM) subroutines are called to update the x, y, and z components of the scattered electric field. These scattered field equations are based upon the development given in [3]. RADEXY, RADEYX (TE) and RADEZX, RADEZY (TM) outer radiation boundary conditions are called next to absorb any outgoing scattered fields. Time is then advanced 1/2 time step according to the Yee algorithm and then the HXSFLD (TM), HYSFLD (TM), AND HZSFLD (TE) subroutines are called to update the x, y, and z components of scattered magnetic field. Time is then advanced another 1/2 step and then either near zone fields are sampled and written to disk in DATSAV, and/or the near zone to far zone vector potentials are updated in SAVFZ. The parameter NZFZ (described later) in the common file defines the type of output fields desired.

After execution of all time steps in the main field update loop, subroutine FAROUT is called if far zone fields are desired to compute the far zone fields and write them to disk. At this point, the execution is complete.

SUBROUTINE SETFZ (TE, TM)

This subroutine initializes the necessary parameters required for far zone field computations. The codes as furnished compute backscatter far zone field and can compute bistatic far zone fields for one scattering angle (i.e. one ϕ angle). Refer to reference [4] for a complete description of the two dimensional near to far zone transformation. Other versions of this subroutine provide for multiple bistatic angles.

SUBROUTINE SAVFZ (TE, TM)

This subroutine updates the near zone to far zone vector potentials.

SUBROUTINE FAROUT (TE, TM)

This subroutine changes the near zone to far zone vector potentials to far zone electric field θ (TM) and ϕ (TE) components and writes them to disk.

SUBROUTINE BUILD (TE, TM) *

This subroutine "builds" the scattering object(s) by initializing the IDONE (TE), IDTWO (TE), and IDTHRE (TM) arrays. The IDONE-IDTHRE arrays are for specifying perfectly conducting and lossy dielectric materials. Refer to Figure 1 for a diagram of the basic two dimensional Yee cell for the TE and TM case. For example, setting an element of the IDONE array at some I,J location is actually locating dielectric material at a cell edge whose center location is I+0.5,J. Thus, materials with diagonal permittivity tensors can be modeled. The default material type for all ID??? arrays is 0, or free space. By initializing these arrays to values other than 0, the user is defining an object by determining what material types are present at each spatial location. Other material types available for IDONE-IDTHRE are 1 for perfectly conducting objects and 2-9 for lossy non-magnetic dielectrics. It is assumed throughout the code that <u>all</u> dielectric materials are non-magnetic (i.e. the materials have a permeability of μ_0). This subroutine also has a section that checks the ID??? arrays to determine if legal material types have been defined throughout the problem space. The actual material parameters (ϵ and σ) are defined in subroutine SETUP. The default geometry is a 0.25 m radius, perfectly conducting cylinder.

The user must be careful that his/her object created in the BUILD subroutine is properly formed.

When it is important to place the object in the center of the problem space, NX and NY should be odd. This is due to the

field locations in the Yee cell and also the placement of the E field absorbing boundary condition surfaces.

If the object being modeled has curved surfaces, edges, etc. that are at an angle to one or more of the coordinate axes, then that shape must be approximately modeled by lines and faces in a "stair-stepped" (or stair-cased) fashion. This stair-cased approximation introduces errors into computations at higher frequencies. Intuitively, the error becomes smaller as more cells are used to stair-case a particular object.

SUBROUTINE DPLATE (TE)

This subroutine builds squares of dielectric material by defining two each of IDONE and IDTWO components corresponding to one spatial square of dielectric material. It can also be used to define thin (i.e. up to one cell thick) dielectric or perfectly conducting wires. Refer to comments within DPLATE for a description of the arguments and usage of the subroutine.

SUBROUTINE SETUP (TE, TM) *

This subroutine initializes many of the constants required for incident field definition, field update equations, outer radiation boundary conditions and material parameters. The material parameters ϵ and σ are defined for each material type using the material arrays EPS and SIGMA respectively. The array EPS is used for the total permittivity and SIGMA is used for the electric conductivity. These arrays are initialized in SETUP to free space material parameters for all material types and then the user is required to modify these arrays for his/her scattering materials. Thus, for the lossy dielectric material type 2, the user must define EPS(2) and SIGMA(2). The remainder of the subroutine computes constants used in field update equations and boundary conditions and writes the diagnostics file.

SUBROUTINE EXSFLD (TE)

This subroutine updates all x components of scattered electric field at each time step except those on the outer boundaries of the problem space. IF statements based upon the IDONE array are used to determine the type of material present and the corresponding update equation to be used.

SUBROUTINE EYSFLD (TE)

This subroutine updates all y components of scattered electric field at each time step except those on the outer boundaries of the problem space. IF statements based upon the IDTWO array are used to determine the type of material present and the corresponding update equation to be used.

SUBROUTINE EZSFLD (TM)

This subroutine updates all z components of scattered electric field at each time step except those on the outer boundaries of the problem space. IF statements based upon the IDTHRE array are used to determine the type of material present and the corresponding update equation to be used.

SUBROUTINES RADEYX, RADEXY (TE) and RADEZX, RADEZY (TM)

These subroutines apply the outer radiation boundary conditions to the scattered electric field on the outer boundaries of the problem space.

SUBROUTINE HXSFLD (TM)

This subroutine updates all x components of scattered magnetic field at each time step. The standard non-magnetic update equation is used.

SUBROUTINE HYSFLD (TM)

This subroutine updates all y components of scattered magnetic field at each time step. The standard non-magnetic update equation is used.

SUBROUTINE HZSFLD (TE)

This subroutine updates all z components of scattered magnetic field at each time step. The standard non-magnetic update equation is used.

SUBROUTINE DATSAV (TE, TM) *

This subroutine samples near zone scattered field quantities and saves them to disk. This subroutine is where the quantities to be sampled and their spatial locations are to be specified and is only called if near zone fields only are desired or if both near and far zone fields are desired. Total field quantities can also be sampled. See comments within the subroutine for specifying sampled scattered and/or total field quantities. When sampling magnetic fields, remember the $\delta t/2$ time difference between E and H when writing the fields to disk. Sections of code within this subroutine determine if the sampled quantities and the spatial locations have been properly defined.

FUNCTIONS EXI, EYI (TE) and EZI (TM)

These functions are called to compute the x, y and z components of incident electric field. The functional form of the incident field is contained in a separate function SOURCE.

FUNCTION SOURCE (TE, TM) *

This function contains the functional form of the incident field. The code as furnished uses the Gaussian form of the incident field. An incident smooth cosine pulse is also available by uncommenting the required lines and commenting out the Gaussian pulse. Thus, this function need only be modified if the user changes the incident pulse from Gaussian to smooth cosine. A slight improvement in computing speed and vectorization may be achieved by moving this function inside each of the incident field functions EXI, EYI and so on.

FUNCTIONS DEXI, DEYI (TE) and DEZI (TM)

These functions are called to compute the x, y and z components of the time derivative of incident electric field. The functional form of the incident field is contained in a separate function DSRCE.

FUNCTION DSRCE (TE, TM) *

This function contains the functional form of the time derivative of the incident field. The code as furnished uses the time derivative of the Gaussian form of the incident field. A smooth cosine pulse time derivative is also available by uncommenting the required lines and commenting out the Gaussian pulse. Thus, the function need only be modified if the user changes from the Gaussian to smooth cosine pulse. Again, a slight improvement in computing speed and vectorization may be achieved by moving this function inside each of the time derivative incident field functions DEXI, DEYI and so on.

SUBROUTINE ZERO (TE, TM)

This subroutine initializes various arrays and variables to zero.

V. INCLUDE FILE DESCRIPTION (TEACOM.FOR, TMACOM.FOR) *

The include files, TEACOM.FOR, TMACOM.FOR, contain all of the arrays and variables that are shared among the different subroutines. These files will require the most modifications when defining scattering problems. A description of the parameters that are normally modified follows.

The parameters NX and NY specify the size of the problem space in cells in the x and y directions respectively. For problems where it is crucial to center the object within the problem space, then NX and NY should be odd. The parameter NTEST defines the number of near zone quantities to be sampled and NZFZ defines the field output format. Set NZFZ=0 for near zone fields only, NZFZ=1 for far zone fields only and NZFZ=2 for both near

and far zone fields. Parameter NSTOP defines the maximum number of time steps. DELX and DELY (in meters) define the cell size in the x and y directions respectively. The ϕ incidence angle (in degrees) is defined by PHINC and the polarization is defined by the code that is being used. Parameters AMP and BETA define the maximum amplitude and the e^{-2} temporal width of the incident pulse respectively. BETA automatically adjusts when the cell size is changed and normally should not be changed by the user. The far zone scattering angle is defined by PHIFZ. The codes as furnished perform backscatter computations, but this parameter could be modified for a bistatic computation.

VI. SCATTERING WIDTH COMPUTATIONS

Companion codes, SWTEA.FOR, SWTMA.FOR, have been included to compute scattering width versus frequency. Each code uses the file name of the FDTD far zone output data (FZOUTTE.DAT, FZOUTTM.DAT) and writes data files of far zone electric field versus time (FZTE.DAT, FZTM.DAT) and scattering width versus frequency (SWTE.DAT, SWTM.DAT). The scattering width computations are performed up to the 10 cell/λ_0 frequency limit. Refer to comments within these codes for further details.

VII. RESULTS

As previously mentioned, the codes as furnished model an infinite, 0.25 m radius, perfectly conducting cylinder and compute backscatter far zone scattered field at an angles of ϕ=180 degrees.

Figures 2-4 show the TM far zone electric field versus time and the scattering width magnitude and phase for the 0.25 m radius perfectly conducting cylinder. Keep in mind that the far zone time domain electric field shown here is <u>not</u> the actual time domain scattered field. The actual far zone time domain scattered field can be obtained by an FFT of the FDTD time domain results, then multiplying the FFT by the appropriate frequency domain factor (described in [4]) and performing an inverse FFT.

Figures 5-7 show the TE far zone electric field versus time and the scattering width magnitude and phase for the 0.25 m radius perfectly conducting cylinder.

VIII. SAMPLE PROBLEM SETUP

The codes as furnished model an infinite, 0.25 m radius, perfectly conducting cylinder and compute backscatter far zone scattered field at an angle of ϕ=180 degrees. The corresponding output data files are also provided, along with codes to compute scattering width using these data files. In order to change the code to a new problem, many different parameters need to be modified. A sample problem setup will now be discussed.

Suppose that the problem to be studied is scattering width backscatter versus frequency from a 0.30 m radius dielectric cylinder with a dielectric constant of $4\epsilon_0$ using a θ-polarized field. The backscatter angle is ϕ=60.0 degrees and the frequency range is up to 3 Ghz.

The incident field is θ-polarized which indicates the TM code must be used. Since the frequency range is up to 3 Ghz, the cell size must be chosen appropriately to resolve the field IN ANY MATERIAL at the highest frequency of interest. A general rule is that the cell size should be 1/10 of the wavelength at the highest frequency of interest. For difficult geometries, 1/20 of a wavelength may be necessary. The free space wavelength at 3 GHz is λ_0=10 cm and the wavelength in the dielectric coating at 3 GHz is 5 cm. The cell size is chosen as 1 cm, which provides a resolution of 5 cells/λ in the dielectric coating and 10 cells/λ_0 in free space. Numerical studies have shown that choosing the cell size $\leq$ 1/4 of the shortest wavelength in any material is the practical lower limit. Thus the cell size of 1 cm is barely adequate. The cell size in the x and y directions is set in the common file through variables DELX and DELY. Next the problem space size must be large enough to accomodate the scattering object, plus <u>at least</u> a five cell boundary (10 cells is more appropriate) on every side of the object to allow for the far zone field integration surface. The default problem space size of 201 by 201 is adequate and provides a 75 cell border around the cylinder. As an initial estimate, allow 2048 time steps so that energy trapped within the dielectric layer will radiate. Thus parameter NSTOP is changed to 2048. If all transients have not been dissipated after 2048 time steps, then NSTOP will have to be increased. Truncating the time record before all transients have dissipated will corrupt frequency domain results. Parameter NZFZ must be equal to 1 since we are interested in far zone fields only. To build the object, simply change the RADIUS variable in the BUILD subroutine to 0.30. In the common file, the incidence angle PHINC has to be changed to 60.0 respectively, and the cell sizes (DELX and DELY) are set to 0.01. Since dielectric material 2 is being used for the dielectric coating, the constitutive parameters EPS(2) and SIGMA(2) are set to $4\epsilon_0$ and 0.0 respectively, in subroutine SETUP. This completes the code modifications for the sample problem.

IX. NEW PROBLEM CHECKLIST

This checklist provides a quick reference to determine if all parameters have been defined properly for a given scattering problem. A reminder when defining quantities within the code: use MKS units and specify all angles in degrees.

TEACOM.FOR, TMACOM.FOR:

1) Is the problem space sized correctly? (NX, NY)

2) For near zone fields, is the number of sample points correct? (NTEST)

3) Is parameter NZFZ defined correctly for desired field outputs?

4) Is the number of time steps correct? (NSTOP)

5) Are the cell dimensions (DELX, DELY) defined correctly?

6) Is the incidence angle (PHINC) defined correctly?

7) For other than backscatter far zone field computations, is the scattering angle set correctly? (PHIFZ)

SUBROUTINE BUILD:

1) Is the object completely and correctly specified?

SUBROUTINE SETUP:

1) Are the constitutive parameters for each material specified correctly? (EPS and SIGMA)

FUNCTIONS SOURCE and DSRCE:

1) If the Gaussian pulse is not desired, is it commented out and the smooth cosine pulse uncommented?

SUBROUTINE DATSAV:

1) For near zone fields, are the sampled field types and spatial locations correct for each sampling point? (NTYPE, IOBS, JOBS)

X. REFERENCES

[1] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," IEEE Trans. Antennas Propagat., vol. AP-14, pp. 302-307, May 1966.

[2] G. Mur, "Absorbing boundary conditions for the Finite-Difference approximation of the Time-Domain Electromagnetic-Field Equations," IEEE Trans. Electromagn. Compat., vol. EMC-23, pp. 377-382, November 1981.

[3] R. Holland, L. Simpson and K. S. Kunz, "Finite-Difference Analysis of EMP Coupling to Lossy Dielectric Structures," IEEE Trans. Electromagn. Compat., vol. EMC-22, pp. 203-209, August 1980.

[4] R.J. Luebbers et. al., "A Two-Dimensional Time-Domain Near Zone to Far Zone Transformation," submitted to IEEE Trans. Antennas Propagat. for publication, May 1991.

XI. FIGURE TITLES

Fig. 1 Standard two dimensional Yee cell showing placement of electric and magnetic fields for the TE and TM case.

Fig. 2 Far zone scattered field versus time for 0.25 m radius perfectly conducting cylinder using TM polarization.

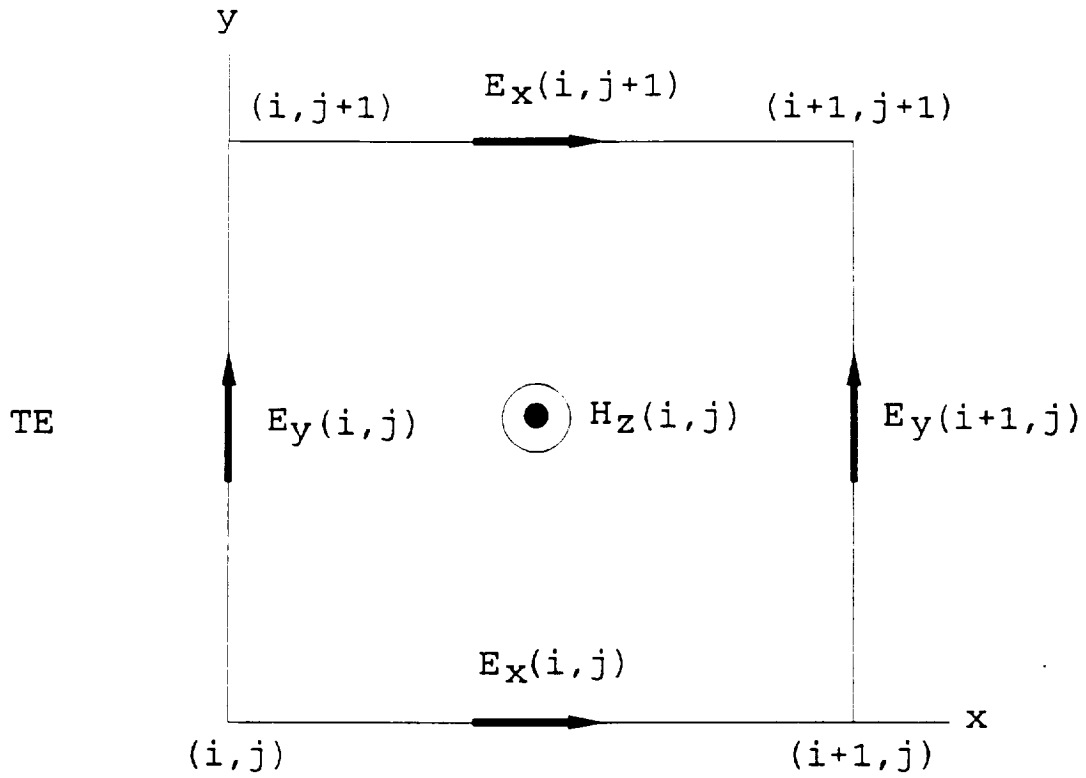
Fig. 3 Scattering width magnitude versus frequency for 0.25 m radius perfectly conducting cylinder using TM polarization.

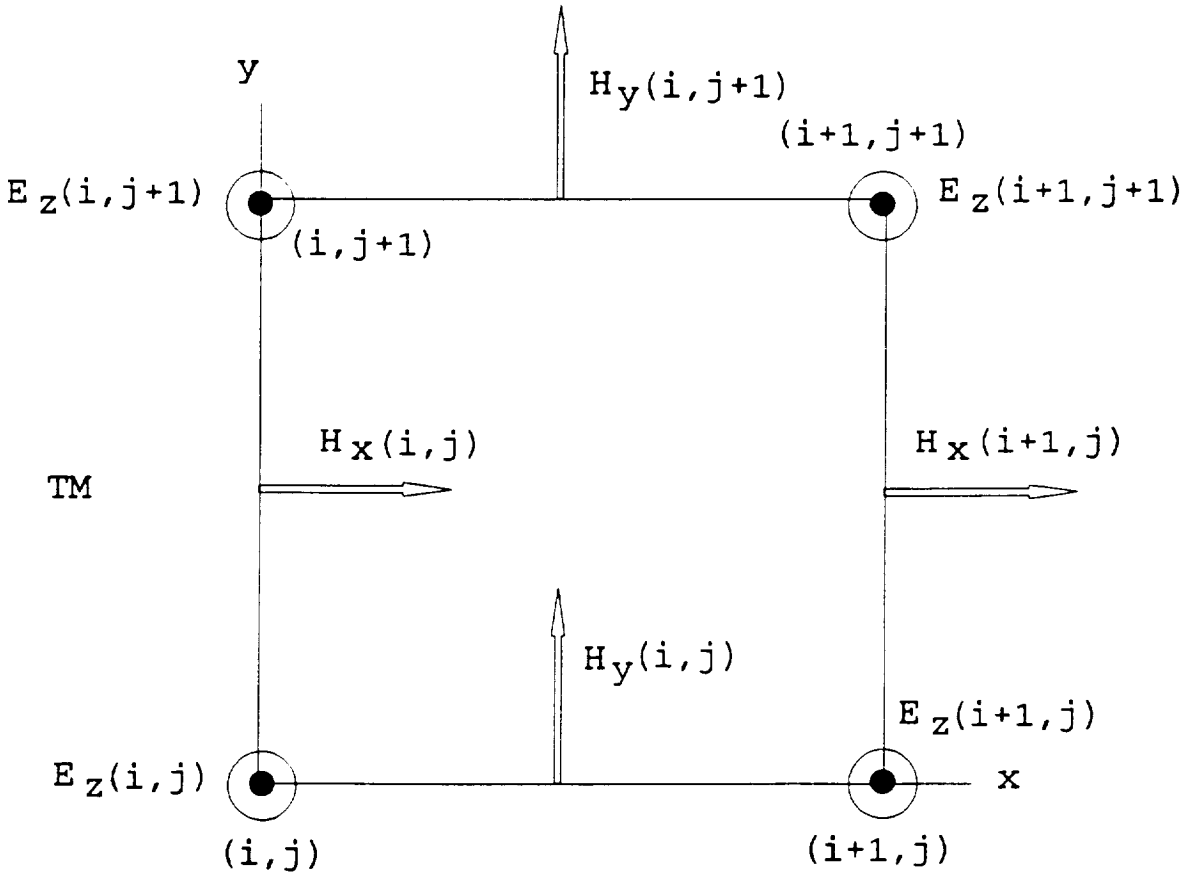
Fig. 4 Scattering width phase versus frequency for 0.25 m radius perfectly conducting cylinder using TM polarization.

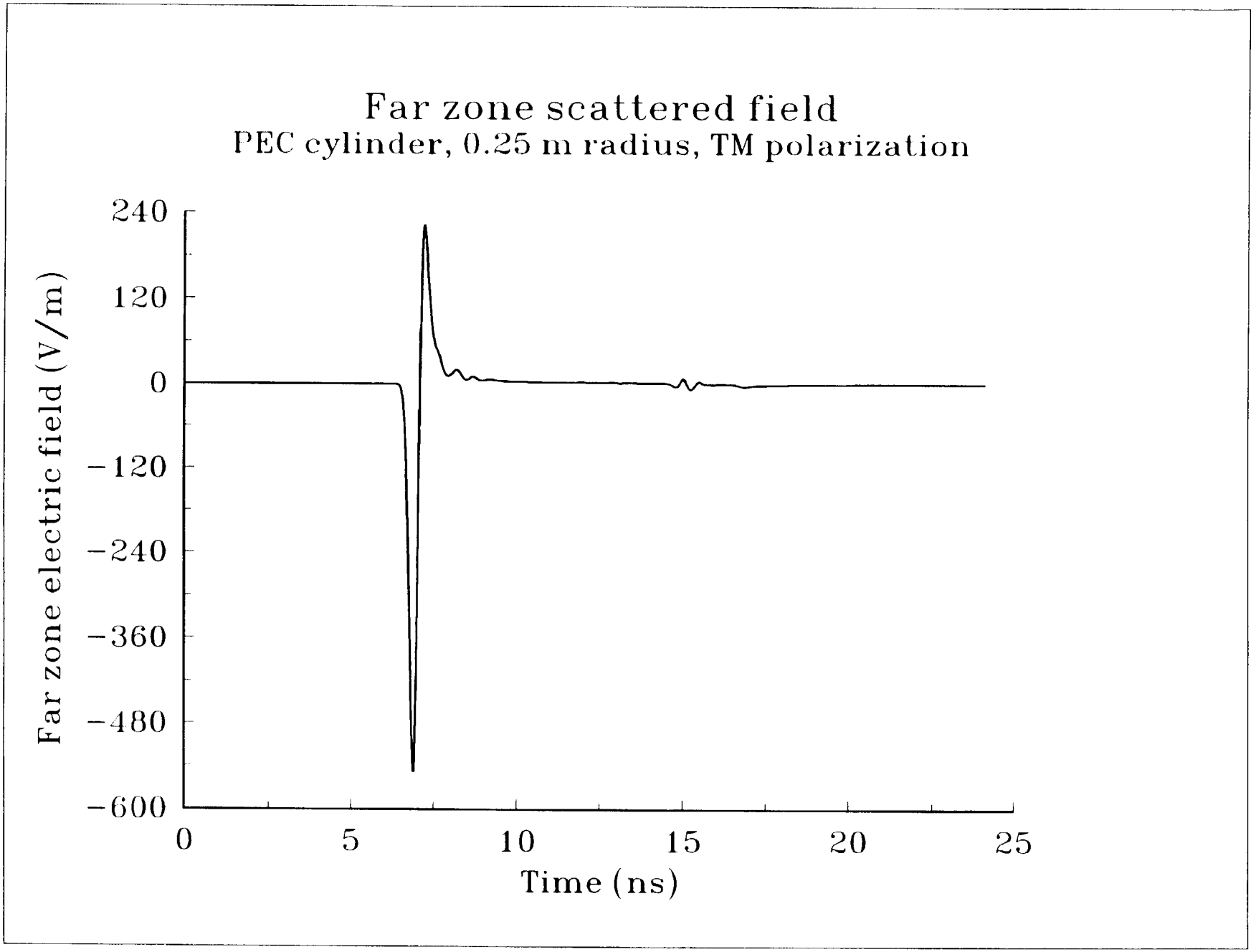
Fig. 5 Far zone scattered field versus time for 0.25 m radius perfectly conducting cylinder using TE polarization.

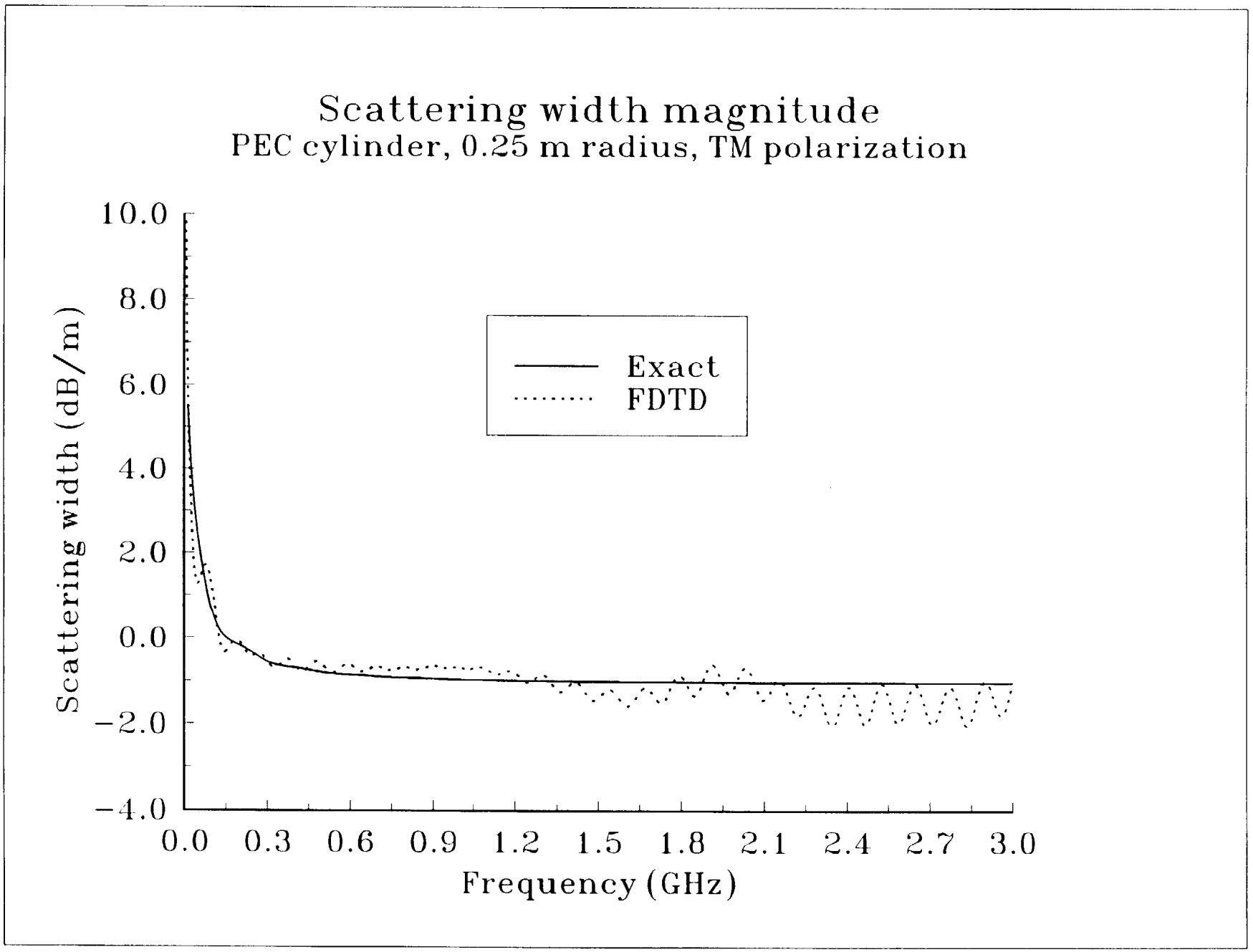
Fig. 6 Scattering width magnitude versus frequency for 0.25 m radius perfectly conducting cylinder using TE polarization.

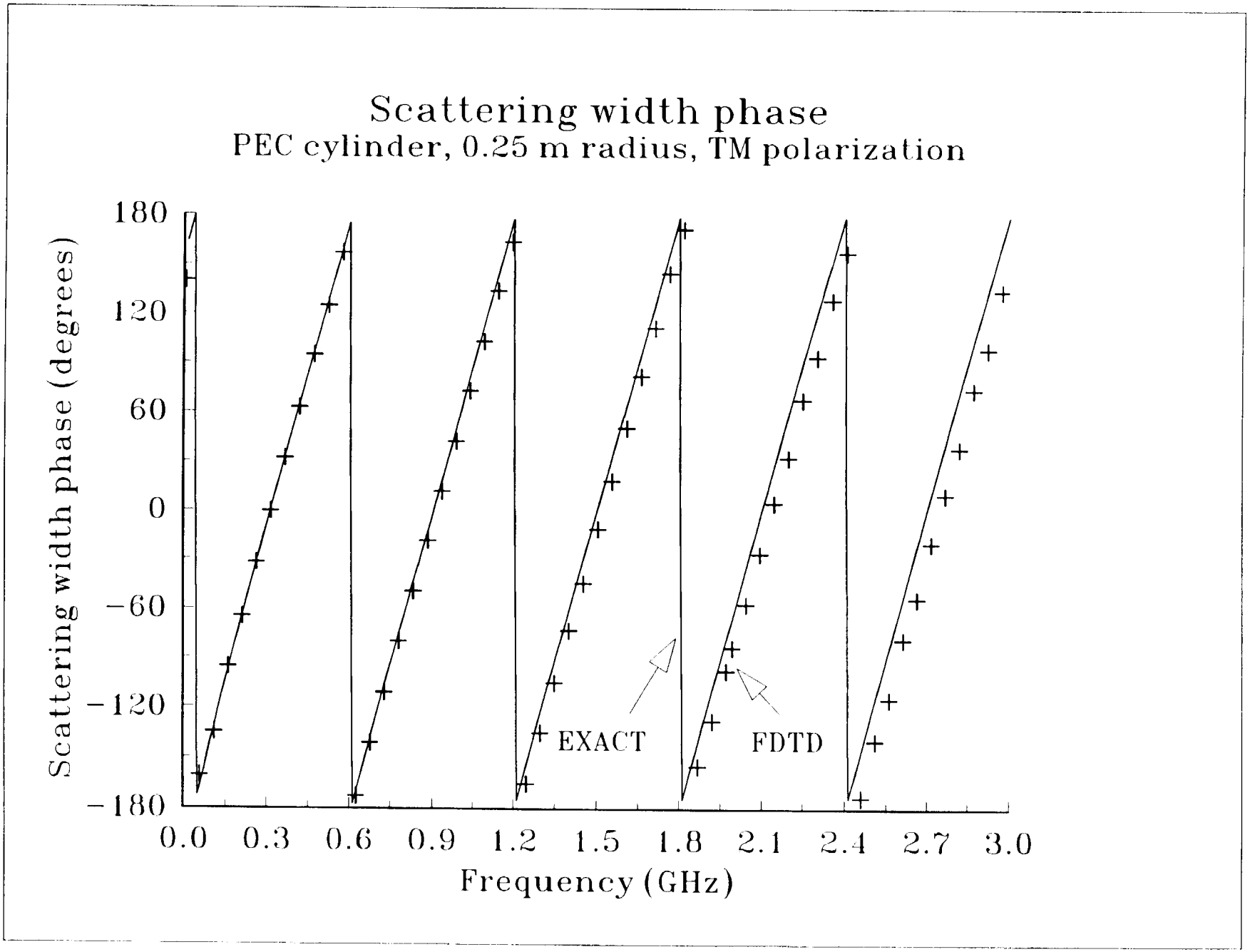
Fig. 7 Scattering width phase versus frequency for 0.25 m radius perfectly conducting cylinder using TE polarization.

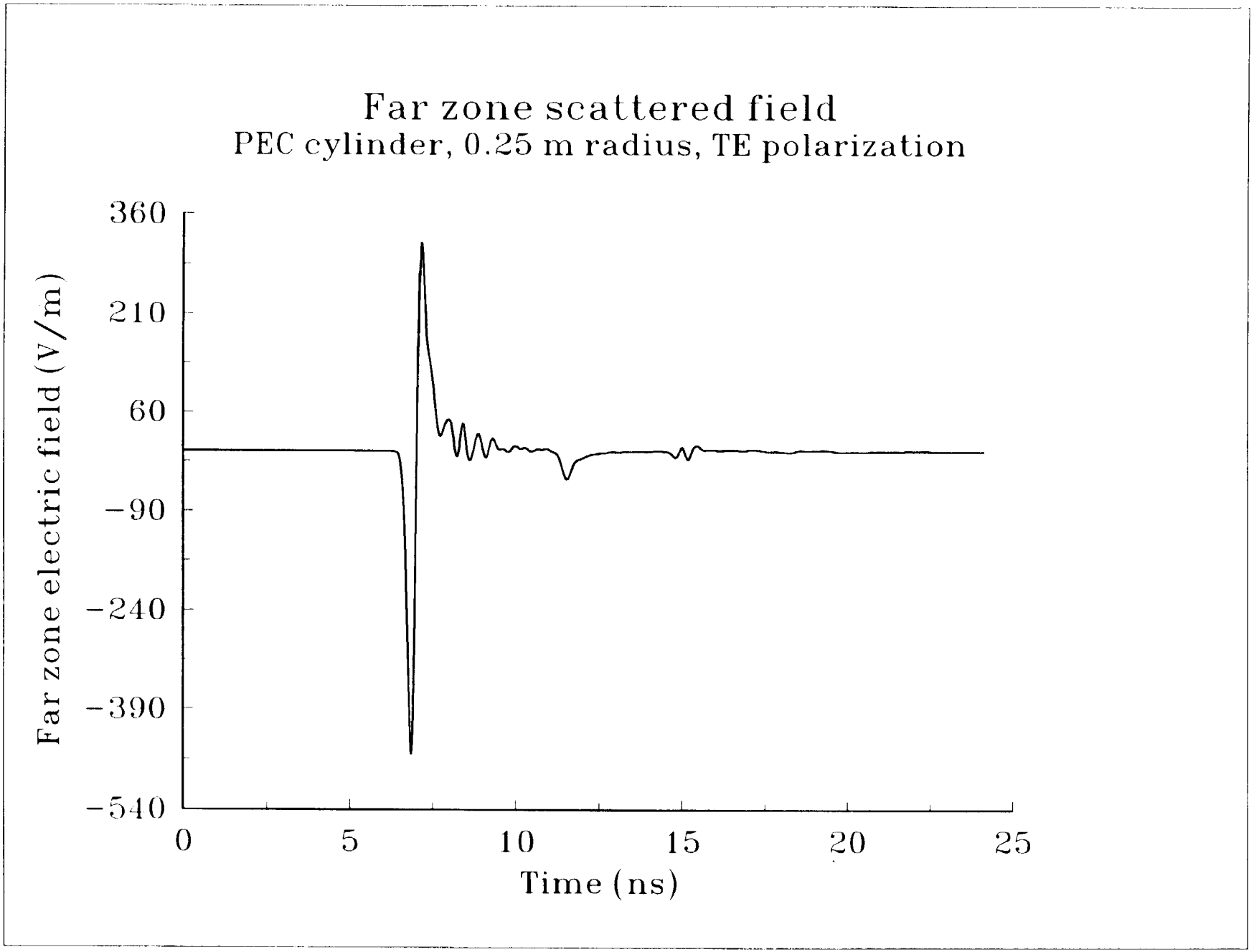

y
(i,j+1)
$E_x(i,j+1)$
(i+1,j+1)
TE
$E_y(i,j)$
$H_z(i,j)$
$E_y(i+1,j)$
$E_x(i,j)$
x
(i,j)
(i+1,j)

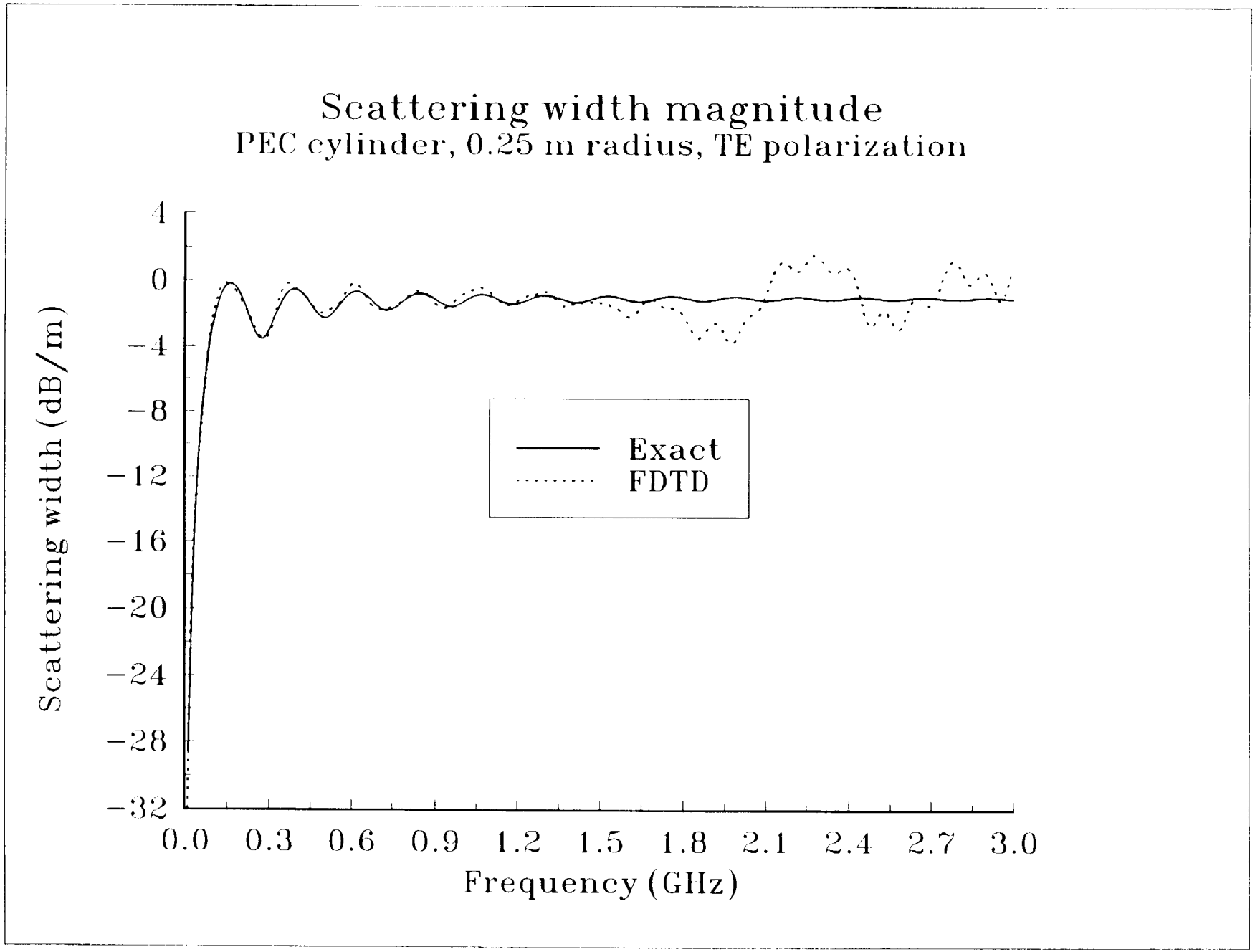

y
$H_y(i,j+1)$
(i+1,j+1)
$E_z(i,j+1)$
$E_z(i+1,j+1)$
(i,j+1)
$H_x(i,j)$
$H_x(i+1,j)$
TM
$H_y(i,j)$
$E_z(i+1,j)$
$E_z(i,j)$
x
(i,j)
(i+1,j)

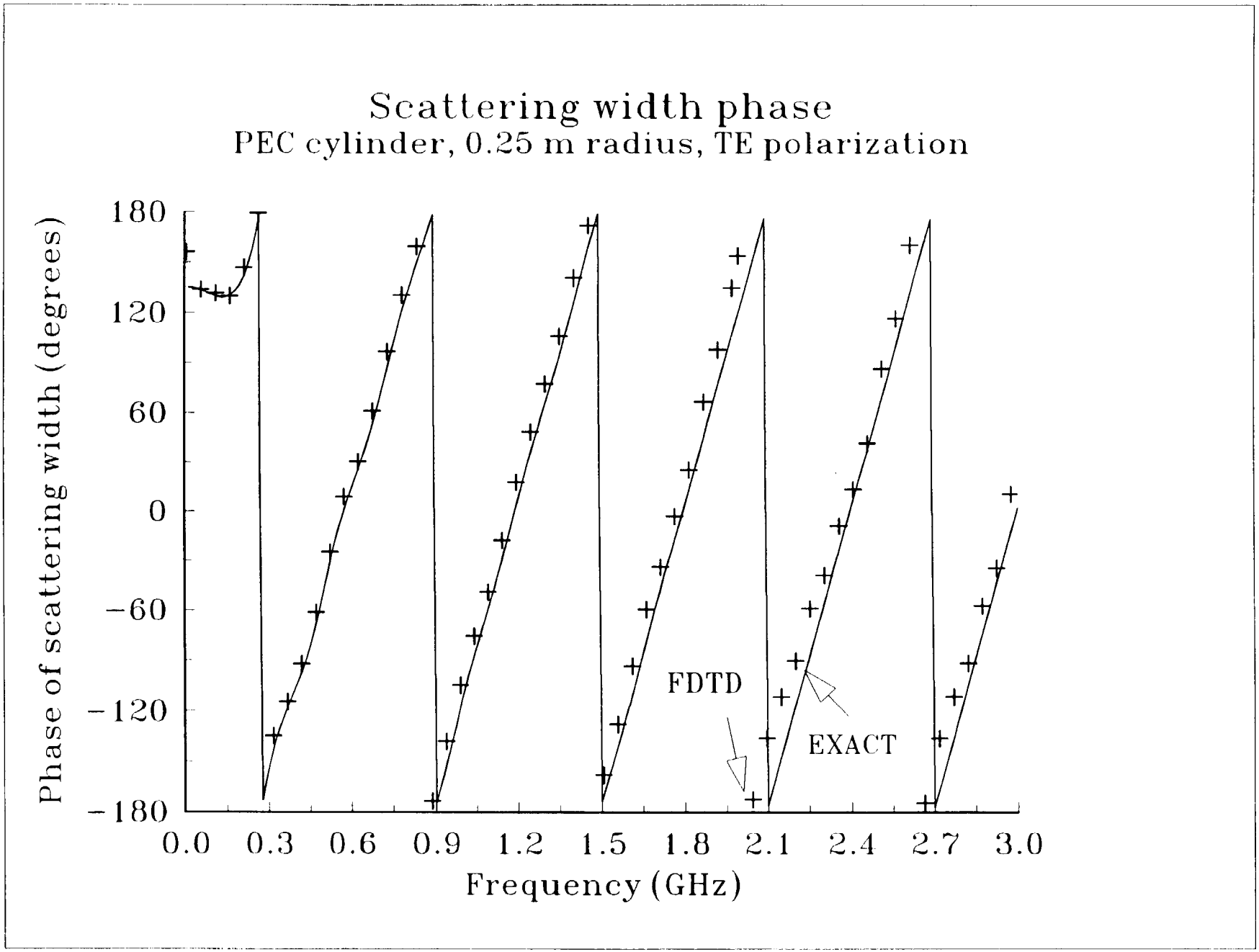

Far zone scattered field
PEC cylinder, 0.25 m radius, TM polarization
Far zone electric field (V/m)
240
120
0
−120
−240
−360
−480
−600
0
5
10
15
20
25
Time (ns)


Scattering width magnitude
PEC cylinder, 0.25 m radius, TM polarization
Scattering width (dB/m)
10.0
8.0
6.0
4.0
2.0
0.0
−2.0
−4.0
Exact
FDTD
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
Frequency (GHz)


Scattering width phase
PEC cylinder, 0.25 m radius, TM polarization
Scattering width phase (degrees)
180
120
60
0
−60
−120
−180
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
Frequency (GHz)
EXACT
FDTD


Far zone scattered field
PEC cylinder, 0.25 m radius, TE polarization
Far zone electric field (V/m)
360
210
60
−90
−240
−390
−540
0
5
10
15
20
25
Time (ns)


Scattering width magnitude
PEC cylinder, 0.25 m radius, TE polarization
Scattering width (dB/m)
4
0
−4
−8
−12
−16
−20
−24
−28
−32
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
Frequency (GHz)
Exact
FDTD


Scattering width phase
PEC cylinder, 0.25 m radius, TE polarization
Phase of scattering width (degrees)
180
120
60
0
−60
−120
−180
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
Frequency (GHz)
FDTD
EXACT